TeV-scale Type-II Seesaw Models and Possible Collider Signatures

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A natural extension of the standard model to accommodate massive neutrinos is to introduce one Higgs triplet and three right-handed Majorana neutrinos, leading to a 6×6 neutrino mass matrix. We show that three light Majorana neutrinos (i.e., the mass eigenstates of ν_e, ν_μ and ν_τ) are exactly massless, if and only if $M_{\rm L} = M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$ exactly holds in this seesaw model. We propose three simple Type-II seesaw scenarios with broken $A_4 \times U(1)_{\rm X}$ flavor symmetry to interpret the observed neutrino mass spectrum and neutrino mixing pattern. Such a TeV-scale neutrino model can be tested in two complementary ways: (1) searching for possible collider signatures of lepton number violation induced by the right-handed Majorana neutrinos and doubly-charged Higgs particles; and (2) searching for possible consequences of unitarity violation of the 3×3 neutrino mixing matrix in the future long-baseline neutrino oscillation experiments.

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The discovery of neutrino oscillations has confirmed the theoretical expectation that neutrinos are massive and lepton flavors are mixed, providing the first evidence for physics beyond the standard model (SM) in particle physics. At present, the seesaw mechanism is the most natural idea to understand the smallness of neutrino masses. However, how to test it has been an open question.

We shall talk about the Type-II seesaw mechanism,[1] which extends the SM with three righ-handed Majorana neutrinos and one Higgs triplet. The effective mass matrix for three light neutrinos is given by $M_\nu \approx M_{\rm L} - M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$. To test the Type-II seesaw model, one possible way is to lower the mass scales of both the heavy neutrinos and the Higgs triplet to the TeV level and allow the Yukawa coupling matrices Y_ν and Y_Δ to be of $\mathcal{O}(10^{-3})$ up to $\mathcal{O}(1)$. Then we may search for the lepton-number-violating signals induced by those heavy particles at the Large Hadron Collider (LHC). In order to generate sufficiently small neutrino masses in this kind of TeV-scale seesaw scenarios, the key point is to adjust the textures of $M_{\rm L}$, $M_{\rm D}$ and $M_{\rm R}$ to guarantee $M_{\rm L} = M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$ in the leading-order approximation. Then tiny but non-vanishing neutrino masses can be ascribed to slight perturbations or radiative corrections to $M_{\rm L}$ and $M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$. We shall prove a no-go theorem: the masses of light Majorana neutrinos are exactly vanishing at the tree level if and only if the global cancellation $M_{\rm L} - M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T = 0$ exactly holds in generic Type-II

seesaw scenarios. Therefore, a feasible way to obtain both tiny neutrino masses and appreciable collider signatures is to allow for an incomplete cancellation between $M_{\rm L}$ and $M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$ terms. We shall propose three simple Type-II seesaw scenarios at the TeV scale by taking into account the $A_4 \times U(1)_{\rm X}$ flavor symmetry and its breaking mechanism, from which the observed neutrino mass spectrum and neutrino mixing pattern can be achieved. We shall also discuss two interesting consequences of this model: (1) possible unitarity violation of the 3×3 neutrino mixing matrix, which can be searched for in the future long-baseline neutrino oscillation experiments; and (2) possible signatures of lepton number violation induced by the right-handed Majorana neutrinos and doubly-charged Higgs particles, which can be searched for at colliders.

We regularize our notations and conventions by reviewing some basics of the Type-II seesaw mechanism. After spontaneous symmetry breaking, the lepton mass terms turn out to be

$$-\mathcal{L}_{\rm mass} = \overline{E_{\rm L}} M_l E_{\rm R} + \frac{1}{2} \overline{(\nu_{\rm L} \;\; N_{\rm R}^c)} \begin{pmatrix} M_{\rm L} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{pmatrix} \nu_{\rm L}^c \\ N_{\rm R} \end{pmatrix} + {\rm h.c.} \,. \tag{1}$$

The overall 6×6 neutrino mass matrix in $\mathcal{L}_{\rm mass}$, denoted as $\mathcal{M}$, can be diagonalized by the unitary transformation $\mathcal{U}^\dagger \mathcal{M} \mathcal{U}^* = \widehat{\mathcal{M}}$; or explicitly,

$$\begin{pmatrix} V & R \\ S & U \end{pmatrix}^\dagger \begin{pmatrix} M_{\rm L} & M_{\rm D} \\ M_{\rm D}^T & M_{\rm R} \end{pmatrix} \begin{pmatrix} V & R \\ S & U \end{pmatrix}^* = \begin{pmatrix} \widehat{M}_\nu & \mathbf{0} \\ \mathbf{0} & \widehat{M}_{\rm N} \end{pmatrix} \,, \tag{2}$$

where $\widehat{M}_\nu = {\rm Diag}\{m_1, m_2, m_3\}$ and $\widehat{M}_{\rm N} = {\rm Diag}\{M_1, M_2, M_3\}$ with m_i and M_i (for $i=1,2,3$) being the light and heavy Majorana neutrino masses, respectively.

In the basis where the flavor eigenstates of three charged leptons are identified with their mass eigenstates, the standard charged-current interactions between ν_α and α (for $\alpha = e, \mu, \tau$) turn out to be

$$-\mathcal{L}_{\rm cc} = \frac{g}{\sqrt{2}} \left[\overline{(e \;\; \mu \;\; \tau)_{\rm L}} V \gamma^\mu \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_{\rm L} W_\mu^- + \overline{(e \;\; \mu \;\; \tau)_{\rm L}} R \gamma^\mu \begin{pmatrix} N_1 \\ N_2 \\ N_3 \end{pmatrix}_{\rm L} W_\mu^- \right] + {\rm h.c.} \,. \tag{3}$$

In a TeV-scale Type-II seesaw model with the complete cancellation between $M_{\rm L}$ and $M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$, it seems that tiny neutrino masses could be generated by the sub-leading terms of M_ν. However, this idea does not work because of the following no-go theorem:[2] *If and only if the relationship $M_{\rm L} = M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$ is exactly satisfied in Type-II seesaw models, then three light Majorana neutrinos must be exactly massless.*

Let us prove the theorem given above. The key point is to replace $M_{\rm L}$ with $M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$ in $\mathcal{M}$, and then the first row of $\mathcal{M}$ can simply be obtained from the second row of $\mathcal{M}$ multiplied by $M_{\rm D} M_{\rm R}^{-1}$ on the left. It follows that the rank of $\mathcal{M}$ must be equal to three (i.e., the rank of $M_{\rm R}$), implying that three light Majorana neutrinos must be exactly massless under the condition of $M_{\rm L} = M_{\rm D} M_{\rm R}^{-1} M_{\rm D}^T$.

To simultaneously achieve tiny neutrino masses and large neutrino mixing angles, we impose the $A_4 \times U(1)_{\rm X}$ flavor symmetry[3] on the Type-II seesaw Lagrangian. In

this case, the assignments of relevant lepton and scalar fields with respect to the symmetry group $SU(2)_{\rm L} \times U(1)_{\rm Y} \otimes A_4 \times U(1)_{\rm X}$ are: $l_{\rm L} \sim (2,-1) \otimes (\underline{3},1)$, $E_{\rm R} \sim (1,-2) \otimes (\underline{1},1)$, $E^{'}_{\rm R} \sim (1,-2) \otimes (\underline{1}',1)$, $E^{''}_{\rm R} \sim (1,-2) \otimes (\underline{1}'',1)$, $\phi \sim (2,-1) \otimes (\underline{1},1)$, $\Phi \sim (2,-1) \otimes (\underline{3},0)$, $\chi \sim (1,0) \otimes (\underline{3},1)$, $\Delta \sim (3,-2) \otimes (\underline{1},2)$, $N_{\rm R} \sim (1,0) \otimes (\underline{3},0)$ and $\Sigma \sim (3,-2) \otimes (\underline{3},0)$, where several triplet scalars have been introduced. Given $SU(2)_{\rm L} \times U(1)_{\rm Y} \otimes A_4 \times U(1)_{\rm X}$ invariance, the Lagrangian responsible for lepton masses reads

$$-\mathcal{L}_{\rm Y} = \sum_\alpha y_e^\alpha (\overline{l_{\rm L}} \tilde{\Phi})_{\underline{\alpha}} E^\alpha_{\rm R} + \frac{y_\Delta}{2} \overline{l_{\rm L}} i\sigma_2 \Delta l^c_{\rm L} + \frac{m_{\rm R}}{2} (\overline{N^c_{\rm R}} N_{\rm R})_{\underline{1}} + y_\nu (\overline{l_{\rm L}} N_{\rm R})_{\underline{1}} \phi + {\rm h.c.} \,. \quad (4)$$

After spontaneous symmetry breaking, the overall neutrino mass matrix $\mathcal{M}$ is determined by its three 3×3 sub-matrices: $M_{\rm L} = m_{\rm L} \cdot \mathbf{1}$, $M_{\rm D} = m_{\rm D} \cdot \mathbf{1}$ and $M_{\rm R} = m_{\rm R} \cdot \mathbf{1}$. In the assumption of $\langle \Phi_1 \rangle = \langle \Phi_2 \rangle = \langle \Phi_3 \rangle$, the charged-lepton mass matrix can be written as $M_l = U_l \widehat{M}_l$, where $\widehat{M}_l = {\rm Diag}\{m_e, m_\mu, m_\tau\} = \sqrt{3} \langle \Phi_i \rangle {\rm Diag}\{y_e, y'_e, y''_e\}$ and U_l can be found in Ref. 2. It is quite obvious that $m_{\rm L} = m^2_{\rm D}/m_{\rm R}$ will lead to $M_{\rm L} = M_{\rm D} M^{-1}_{\rm R} M^T_{\rm D}$. According to the no-go theorem, this complete cancellation makes light neutrino masses exactly vanishing. To obtain the realistic neutrino mass spectrum and lepton flavor mixing pattern,[4] we may introduce an incomplete cancellation between $M_{\rm L}$ and $M_{\rm D} M^{-1}_{\rm R} M^T_{\rm D}$ terms by breaking the flavor symmetry $U(1)_{\rm X}$ explicitly to Z_2. We may assign the proper Z_2 parity to produce slight perturbations to the neutrino mass terms. There are three simple possibilities:[2] (1) perturbations to $M_{\rm L}$, i.e., $l_{\rm L}$, $E_{\rm R}$, $E'_{\rm R}$, $E''_{\rm R}$, χ and ϕ are odd under the Z_2 transformation, while the other fields are even under the same transformation; (2) perturbations to $M_{\rm D}$, i.e., $l_{\rm L}$, χ, Σ and ϕ are odd under the Z_2 transformation, while the other fields are even under the same transformation; and (3) perturbations to $M_{\rm R}$, i.e., $l_{\rm L}$, $E_{\rm R}$, $E'_{\rm R}$, $E''_{\rm R}$, Σ and ϕ are odd under the Z_2 transformation, while the other fields are even under the same transformation. Each of them is compatible with current neutrino oscillation data. A more general approach should include the perturbations to $M_{\rm L}$, $M_{\rm D}$ and $M_{\rm R}$ together. Then the Type-II seesaw formula can be re-expressed as

$$M_\nu \approx \delta M + \delta M_{\rm L} + \tilde{M}_{\rm D} \tilde{M}^{-1}_{\rm R} \delta M_{\rm R} \tilde{M}^{-1}_{\rm R} \tilde{M}^T_{\rm D} - \tilde{M}_{\rm D} \tilde{M}^{-1}_{\rm R} (\delta M_{\rm D})^T - \delta M_{\rm D} \tilde{M}^{-1}_{\rm R} \tilde{M}^T_{\rm D} \,, \quad (5)$$

where $\delta M_{\rm L,D,R}$ is the perturbation term of $M_{\rm L,D,R}$, and δM denotes the residue of the incomplete cancellation between $M_{\rm L}$ and $M_{\rm D} M^{-1}_{\rm R} M^T_{\rm D}$ terms.

Now we proceed to discuss the unitarity violation and collider signatures in the Type-II seesaw model. The non-unitarity of the lepton flavor mixing matrix V is actually a common feature of the seesaw models, as one can easily see from $VV^\dagger = \mathbf{1} - RR^\dagger \neq \mathbf{1}$. In practice, one may resort to a recursive expansion[5] of M_ν in powers of $M_{\rm D} M^{-1}_{\rm R}$ and then obtain $\xi \equiv RR^\dagger \approx {U_l^\dagger}^2 M_{\rm D} M^{-1}_{\rm R} (M^{-1}_{\rm R} M^T_{\rm D})^* {U_l}^2$, where U_l is the unitary matrix used to diagonalize M_l. Note that ξ is in general complex and may give rise to some additional CP-violating effects in neutrino oscillations.[6] In our specific scenarios discussed above, however, we find $\xi \approx m^2_{\rm D}/m^2_{\rm R} \cdot \mathbf{1}$. Thus there is almost no extra CP violation induced by the unitarity violation of V. Translating

the numerical results of Refs. 6-8 into the restriction on ξ in our language, we obtain

$$|\xi| = \begin{pmatrix} |\xi_{ee}| < 1.1 \cdot 10^{-2} & |\xi_{e\mu}| < 7.0 \cdot 10^{-5} & |\xi_{e\tau}| < 1.6 \cdot 10^{-2} \\ |\xi_{\mu e}| < 7.0 \cdot 10^{-5} & |\xi_{\mu\mu}| < 1.0 \cdot 10^{-2} & |\xi_{\mu\tau}| < 1.0 \cdot 10^{-2} \\ |\xi_{\tau e}| < 1.6 \cdot 10^{-2} & |\xi_{\tau\mu}| < 1.0 \cdot 10^{-2} & |\xi_{\tau\tau}| < 1.0 \cdot 10^{-2} \end{pmatrix} \quad (6)$$

at the 90% confidence level.

A direct test of the seesaw mechanism requires the unambiguous observation of heavy Majorana neutrinos. The clearest signature induced by N_i should be the lepton-number-violating process $pp \to W^\pm \to \mu^\pm N \to \mu^\pm \mu^\pm jj$ at the LHC. [9] It can be resonantly enhanced due to the on-shell production of heavy Majorana neutrinos. We feel that the discovery of heavy majorana neutrinos with $M_i \sim \mathcal{O}(10^2)$ GeV to $\mathcal{O}(1)$ TeV and $\xi_{\mu\mu} \sim \mathcal{O}(10^{-3})$ to $\mathcal{O}(10^{-2})$ is possible. For the doubly charged scalars existing in the Type-II seesaw model, one may concentrate on the pair production in the Drell-Yan process $q\bar{q} \to \gamma^*/Z^* \to \Delta^{\pm\pm}\Delta^{\mp\mp}$[10] and the subsequent decays $\Delta^{\pm\pm} \to W^\pm W^\pm$ or $\Delta^{\pm\pm} \to l^\pm l^\pm$. The doubly charged scalars can be observed at the LHC with a branching fraction $\sim$ 50% up to the mass range of 800 GeV to 1 TeV. In our model, the choice of $y_\Delta \sim \mathcal{O}(1)$ and $\langle \Delta \rangle \sim 1$ GeV will extend the above mass range for the doubly-charged scalars.

In short, the main concern of this talk is the experimental testability of the seesaw mechanism in the era of the LHC and precision neutrino experiments. We find that the naturalness of the Type-II seesaw mechanism might be partly lost at the TeV scale, just like that of the Type-I seesaw mechanism at this energy region.[11] More theoretical and phenomenological effort is desirable in order to bridge the gap between light and heavy Majorana neutrinos.

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